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The investigation of CO_2 storage potential in the Algoa basin in South Africa

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Abstract

Carbon capture and storage (CCS) is seen as one of the technical approaches that can be used to mitigate global climate change in fossil fuel dominated countries such as South Africa. Approximately 90% of primary energy in South Africa is derived from fossil fuels, with coal providing 92% of electricity production in the country. The South African Centre of Carbon Capture and Storage (SACCCS) was established in 2009 (by the South African government with the assistance from international governments and industry) to investigate the potential of CCS in the country. SACCCS is addressing its mandate in line with the South African CCS Roadmap, which has been endorsed by the South African government.

SACCCS's role in the South African CCS Roadmap is as follows:

2004	Assessment of the potential for CCS in South Africa
2010	Development of a South African CO_2 Geological Storage Atlas
2017	Commencement of a Pilot CO_2 Storage Project *(10,000 - 50,000t CO_2 stored)*
2020	Facilitate the commencement of a CCS demonstration plant *(in the order of 100,000t CO_2/year)*
2025+	Inform the implementation of commercial CCS deployment *(over 1,000,000t CO_2/year)*
Ongoing:	*Provide support to other CCS activities in South Africa*

The results from the assessment of CCS potential in South Africa were summarised and documented in the Atlas (which was published in 2010) with the majority of storage potential occurring in Mesozoic basins of South Africa. There is 150 Gt of theoretical storage capacity is identified, of which 98% occurs offshore. After the completion of the Atlas the next stage on the

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Roadmap, the Pilot CO_2 Storage Project (PCSP), has become the focus of SACCCS activities. The scope and available funding of the PCSP led to the decision to focus on the onshore portions of the Algoa and Zululand basins as possible sedimentary basins for the PCSP programme.

This paper will discuss the progress associated with the ongoing investigation of CO_2 storage potential in the Algoa basin which forms the onshore extension of the offshore Outeniqua basin. The middle Jurassic (Kimmeridgian) to lower Cretaceous (Hauterivian) Uitenhage Group constitutes the syn-rift basin-fill succession with stratigraphy dominated by the fluviatile Kirkwood Formation, and shallow marine Sundays River Formation. Due to limited and reasonably poor data availability, the need for new data and more tests on existing data to confirm any potential storage areas/sites was cited. SACCCS is now planning additional analysis of data to potentially allow for reinterpretation of the older data. The results from the analysis and reinterpretation will inform the next stage of the PCSP.

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Keywords: CO_2; CCS; South Africa; SACCCS; Council for Geoscience

1. Introduction

Approximately 90% of primary energy in South Africa is derived from fossil fuels, with coal providing 92% of electricity production in the country [1]. Carbon capture and storage (CCS) was introduced in South Africa as one of the technical approaches used to mitigate global climate change. In 2009 the South African government, with the assistance from international governments and industry, established the South African Centre of Carbon Capture and Storage (SACCCS) to investigate the potential of CCS in the country. SACCCS is addressing its mandate in line with the South African CCS Roadmap, which has been endorsed by the South African government. The Roadmap for CCS provides a phased outline for the work required to achieve a thorough understanding of the technical potential of CCS technology in South Africa.

SACCCS's role in the South African CCS Roadmap is as follows:

2004	Assessment of the potential for CCS in South Africa
2010	Development of a South African CO_2 Geological Storage Atlas
2017	Commencement of a Pilot CO_2 Storage Project (10,000 - 50,000t CO_2 stored)
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2025+	Inform the implementation of commercial CCS deployment (over 1,000,000t CO_2/year)
Ongoing	Provide support to other CCS activities in South Africa

A country-scale assessment into CO_2 storage potential was undertaken to better understand the potential for CO_2 storage in the country, the results of which were summarized and documented in the Atlas on Geological Storage of Carbon Dioxide in South Africa (Atlas) [2]. The majority of the storage potential was found to lie in the Mesozoic basins of South Africa (Figure 1) with a theoretical storage capacity concluded to be ~150 Gt of which 98% occurs offshore in the combined capacity of the Outeniqua basin (south coast), the Orange basin (west coast) and the Durban and Zululand basins (east coast), with the remaining 2% onshore. Of the onshore storage capacity, about 1% is recorded for the deep 'unmineable' coal seams of South Africa with a rough equal split of the remaining 1% capacity between the Zululand and Algoa basins. Though majority of the storage lies offshore, scope and available funding led to the decision to focus on the onshore portions of storage capacity.

2. Basin-Scale Assessment Methodology

With the completion of the Atlas, SACCCS is focused upon the Pilot CO_2 Storage Project (PCSP). In 2012 SACCCS commissioned the Council of Geoscience and Petroleum Agency of South Africa (PASA) to undertake a basin-scale assessment of the identified onshore basins to define their individual CO_2 storage prospectivity [3]. The contractors collaborated on a desktop study that comprised published literature as well as maps, original reports, borehole logs and 2D seismic data interpretations acquired from oil and gas exploration in the onshore Algoa basin.

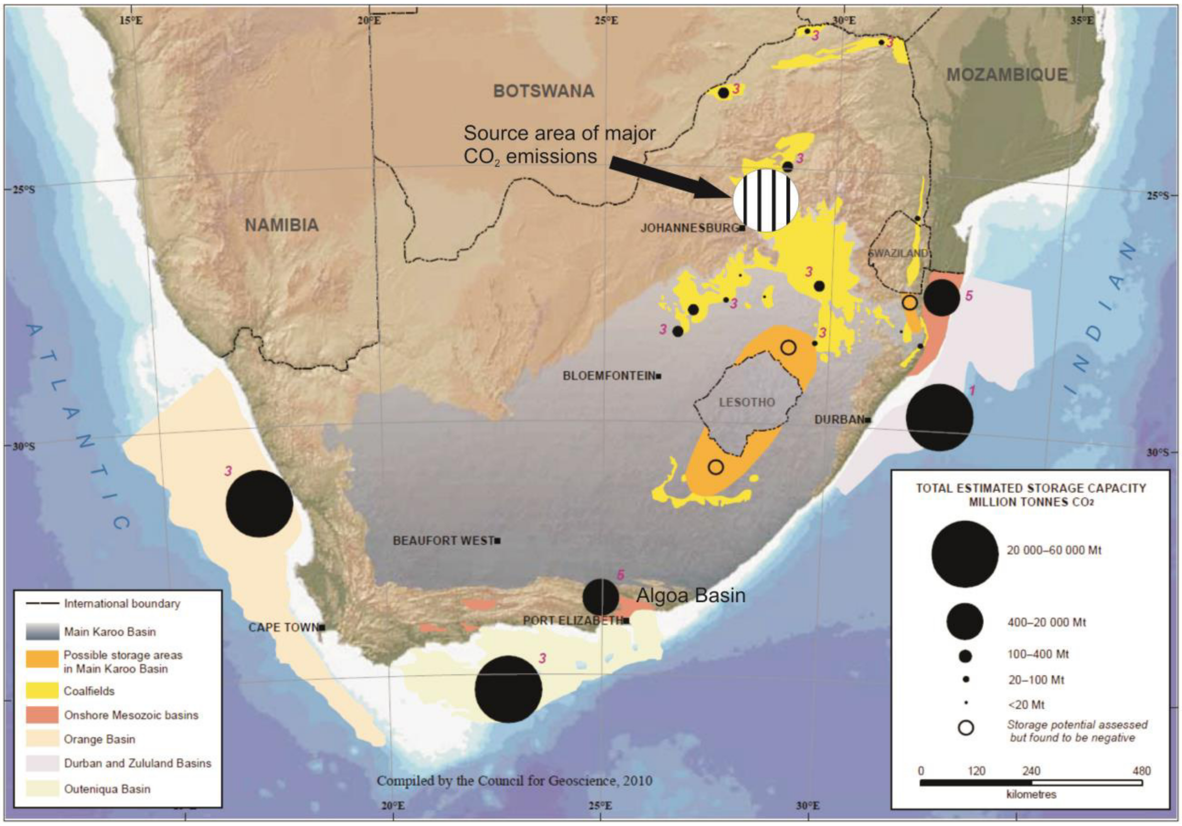

Figure 1: Possible storage opportunities within deep saline formations in South Africa. Data confidence ranked out of 5 is represented by purple figures in each basin. [modified after 3].

The onshore Algoa basin north-east of Port Elizabeth (Figure 1), was the focus of hydrocarbon exploration during the 1960's to 1980's, and is traversed by 1117.85 km of 2D seismic profiles with 24 exploration boreholes having been drilled, to depths of between 700 and 4600 m. Data availability are however a significant issue, with well completion reports, engineering reports, lithology logs and log analysis reports available for only ten wells, and with no data available for the remaining 14 wells. Although some downhole tests were undertaken during exploration, it must be noted that many failed or were incomplete, with little to no qualitative data being available for the basin. Depth limits for the assessment were set at optimum depths of 800–2500 m for CO_2 storage. The study utilized existing information to delineate potential sandstone reservoirs as well as their potential rock volume for the safe storage of CO_2.

All available stratigraphic logs were remapped with sandstone units greater than 30 m in thickness, below 800 m depth being considered. Due to the poor seismic resolution of the seismic data reservoirs and cap rock packages thinner than 30 m in thickness could not be identified on the seismic profiles. The detailed lithology logs produced by SOEKOR were therefore re-logged and simplified to indicate possible reservoirs greater than 30 m in thickness using a cut-off ratio of 50% sandstone (Table 1). This ratio serves as an average ratio for sandstone packages and does not take into account thin lenses within a larger package.

Table 1: Cut-off ratios for sandstone, siltstone and shale lithologies logged in the Algoa basin.

Sandstone %	Siltstone %	Shale %	Final Lithology
50	40	10	Sandstone
30	60	10	Siltstone
0	10	90	Shale

Digital data for well location and geophysical logs were integrated with the seismic data in IHS Kingdom® Suite with borehole logs re-digitized to aid production of detailed cross sections within the seismic profiles. Sandstone bodies identified within borehole and geophysical logs were correlated with seismic reflectors and their extent mapped across the basin. The subdued nature of the geophysical logs is due to a large percentage of siltstone in the successions, resulting in a lack of distinct geophysical signature variance between sedimentary lithologies, however where present, sandstone-shale packages can be delineated. By combining the lithological and gamma ray geophysical logs it was possible to correlate and subdivide the sandstone and siltstone packages. The gamma ray logs were combined with lithological logs to define the average thicknesses of each sandstone/shale package. No detailed basin-scale 2D or 3D cross sections have been completed for the Algoa basin as geophysical correlation was not possible between the separate depositional areas within the Algoa basin as the lithologies vary laterally, alternating between shale and sandstone lenses, or are structurally controlled. Throughout the basin no detailed geological data on caprock are available.

In many instances, only partial data were available for selected areas within the basin, thereby hampering definition of potential reservoirs. An example can be made comparing the Nanaga and Seaview areas, where Nanaga has no available geological logs and mapping was undertaken using gamma ray logs, whilst the Seaview and Alexandria areas have no available geophysical logs and mapping was undertaking by seismic reflector mapping paired with available geological logs.

3. Basin-Scale Assessment Results

The Algoa basin is one of several Mesozoic sedimentary basins located along the south-eastern margin of South Africa, where it forms a 3900 km^2 onshore extension of the large offshore Outeniqua basin. The Algoa basin consists of a series of rift-related half-graben structures (Figure 2) which formed between ~155–135 Ma [4] as the result of extensional tectonic episodes during the initial break-up of Gondwana in the Mid-Jurassic. The basin is represented by a composite structure composed of two curved half grabens, the Uitenhage and Sundays River Troughs with offshore extensions [5]. Although the basin is highly compartmentalized with irregular basin-floor depths, the Sundays River Trough forms the main portion of the basin, deepening towards the coastline attaining depths greater than 3000 m (Figure 2) with ~4160 m of basin-fill successions identified in borehole AL 1/69.

Basin-fill lithologies comprise the Uitenhage and overlying Algoa Groups. The Uitenhage Group contains the majority of the succession, deposited as syn-rift sediments during a period in which the basin was actively developing. The Uitenhage Group is subdivided into three formations, the Enon, Kirkwood and Sundays River Formations. The lowermost Enon Formation consists of fluvial conglomerates and minor sandstones developed as piedmont fans along the margin of the basin and do not host potential for CCS due to its geology and limited extent.

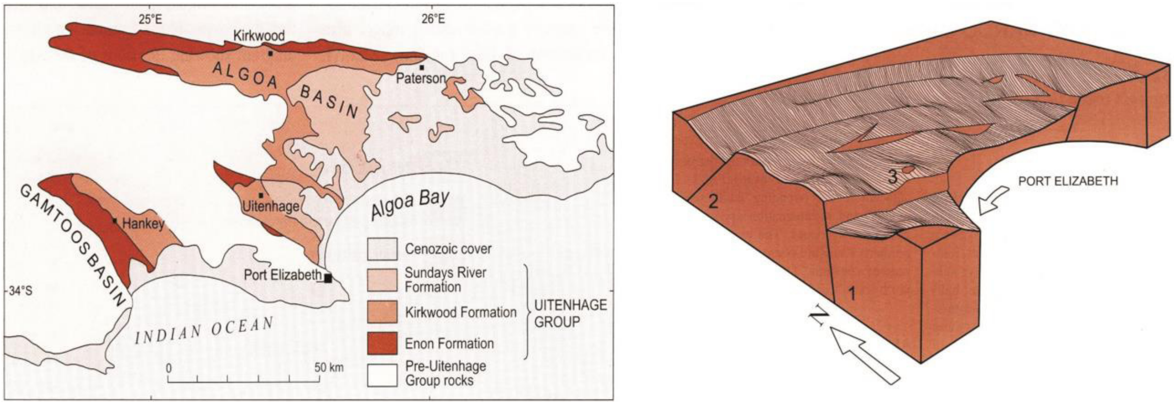

Figure 2: Geology and structure of the Algoa basin. Note the compartmentalized nature of the basin with the Sundays River Trough (2) separated from the Uitenhage Trough (1) by the Addo Nose (3) [after 6].

At depth within the central portion of the Sundays River Trough, the Enon Formation is not developed, with brackish shales, siltstones and sandstone of the Kirkwood Formation directly overlying basement lithologies. The Kirkwood Formation attains a maximum thickness exceeding 2200 m at the seaward end of the Sundays River Trough, and consists of variegated, reddish-brown, pink or green-grey silty mudstone interbedded on various scales with sandstone [6]. The sandstone is coarse- to medium-grained, yellow-buff to pale grey (Figure 3). Inclined point-bar sandstone beds are present in a setting of normal grading, ranging from pebbly conglomerate at the base to mudstone at the top of each bedset. Although the ratio of sandstone to shale decreases towards the sub-trough axes of the Algoa basin, the number of sandstone beds >3 m in thickness increases from 20 to 60 towards the trough axes within the deeper portions of the basin [7]. Where developed at depth, these porous and marginally permeable terrestrial sandstones represent potentially prospective horizons for CCS.

In the subsurface the Kirkwood Formation contains two members that are absent or very poorly exposed in surface outcrop. These are the Colchester and Swartkops Members. The Colchester Member developed within the Sundays River Trough comprises dark grey, waxy shale that provided oil shows in the Sundays River Trough [7].

The uppermost unit of the Uitenhage Group is defined by the shallow marine to estuarine Sundays River Formation, represented by a succession of thin, grey sandstones interbedded with siltstone and mudstone, containing a variety of marine fossils [6]. As with the underlying Kirkwood Formation; the Sundays River Formation thickens along the trough axis and towards the east, reaching a thickness exceeding 1800 m at the seaward end of the onshore Sundays River Trough. Shale/sandstone ratios within the Sundays River Formation decrease substantially from 0.5 along the margin of the Sundays River Trough, to 0.063 at the sub-trough axes [7]. Because sand deposition in the marine environment concentrates in the shallow-coastal zone, the number of sandstone beds exceeding 3 m thick decreases from 80 near the outcrop margin to 10 in the Sundays River Trough [7]. Similarly the total thickness of sandstone, in beds exceeding 3 m thick, also decreases towards the basin troughs.

Figure 3: Kirkwood Formation – interbedded porous medium to coarse-grained sandstones overlying maroon shales (images courtesy J.S.V. Reddering)

The faulted nature of the basin combined with the fluvial nature of the Kirkwood Formation, makes continuous correlation of individual sandstone units exceptionally difficult. These restricted distributions of diverse sediment types are typically due to highly confined basin subsidence which was due to sporadic movement on the major bounding faults, as a reaction to the pull-apart tectonic regime sustained during the break up of Gondwana [8].

4. Basin-Scale Assessment Discussion

4.1. Storage Potential of the Algoa basin

Seven prospective areas were identified in the onshore Algoa basin, of which six occur within the Sundays River Trough and one within the Uitenhage Trough. The Uitenhage Trough was removed as a prospective CO_2 storage region due to the region being declared a Subterranean Groundwater Control Area [9] with very low salinity and relatively shallow groundwater reservoirs. The Sundays River Trough was therefore defined as the only area with potential storage capacity in the onshore Algoa basin.

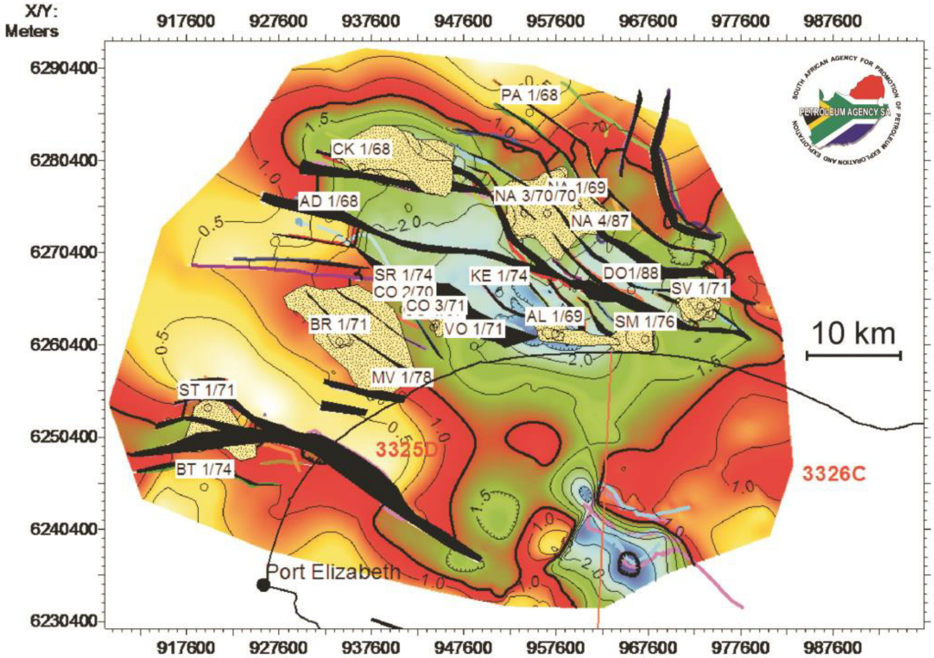

Figure 4: Sandstone reservoirs mapped within the Algoa basin. Faulting is defined by the thick black lines indicating that many of the reservoirs are structurally bound. Basin depth is defined by coloured contour plot with yellow being near surface and blue being deep portions of the basin. Depth contours are in two-way time [after 3].

The six prospective areas within the Sundays River Trough are defined around existing wells, which were used as control points from which potential sandstone packages were mapped (Figure 4; Table 2). Three regions/sites hosted numerous, laterally extensive sandstone packages deposited along the contact between the Kirkwood and Sundays River Formations. These regions were defined as the Addo Trough (a large sub-basin within the northern part of the Sundays River Trough defined by a south-plunging half graben north of the Commandokraal fault), the Colchester Trough (an east-plunging unit on the margin of the southeastern Sundays River Trough) and the Nanaga Anticline (situated above a basement high on the northern flank of the main Addo Syncline within the Sundays River Trough). Three sites hosting sandstone packages with more limited lateral extent were also identified, namely the Seaview Structure, the Alexandria and Springmount areas. Although each of the six prospects have numerous sandstone packages identified at varying depths, some were not considered as having CCS prospectivity due to limitations defined by porosity and permeability variations with depth. Storage capacity estimates were made for each prospect and were assessed and ranked for their suitability for PCSP areas on the basis of storage capacity, injectivity, containment, site logistics and the presence of natural underground resources (Table 3).

Although a large amount of vital reservoir data are lacking within the basin, a static method calculation based upon the CO_2 storage capacity of deep saline reservoirs [10] was undertaken to estimate the potential capacity of the identified sandstone reservoirs within the mapped areas.

The following formula was utilized or calculation purposes:
$M_{CO2} = A_t \, h_g \, \varphi_{tot} \, \rho \, E$ (see Table 2).

Table 2: Volumetric equation parameters for calculation of CO_2 storage capacity in deep saline formations [10].

Parameter	Units*	Description
M_{CO2}	M	Mass estimate of saline formation CO_2 storage capacity.
A_t	L^2	Geographical area that defines the basin or region being assessed for CO_2 storage calculation.
h_g	L	Gross thickness of saline formations for which CO_2 storage is assessed within the basin or region defined by A.
φ_{tot}	L^3/L^3	Average porosity of entire saline formation over thickness h_g or total porosity of saline formations within each geological unit's gross thickness divided by h_g.
P	M/L^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions anticipated for a specific geological unit averaged over h_g. See Figure 3.1.
E**	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO_2 [Viljoen et al. (2010) stipulates that for South African basins for which net storage areas and thicknesses data are used, this factor should vary from 0,04 to 0,16 for deep saline reservoir storage.]

* L is length; M is mass.

It must be noted that inaccuracy is inherent within the calculations as the estimate depends on specific reservoir data, some of which is limited or not available. It is therefore suggested that if additional information be acquired, the estimates be recalculated accordingly. Although a geometrical factor is used in the formula when storage occurs in a depleted oil and gas reservoir, it is usually not used for storage in saline reservoirs, since it is incorporated in the efficiency factor. CO_2 trapping mechanisms such as, structural/stratigraphic trapping, hydrodynamic trapping, residual trapping, solubility trapping and mineral trapping [11], are important factors as they influence the storage volume and storage volume assessment method [12]. A further important factor to take into account is whether storage occurs in a closed, open or semi-closed system. No refinement of calculations was made in this study to incorporate the different trapping mechanisms, permeability and pressure conditions in the reservoir [13; 14; 12].

Due to the uncertainty of the value for the efficiency factor, two scenarios with efficiency factors of 4% and 1% were used. The results and associated rankings of the identified areas are presented in Table 3. Rankings were based upon a number of criteria including potential capacity; injectivity (permeability); containment (salinity); logistics (injection depth); resources (proximity to urbanization). Little to no data are available regarding the sealing capacity of the overlying shale units within the basin. Additional work will need to be undertaken to determine if there is suitable sealing capacity necessary for storage. As relevant reservoir data are missing or downhole experiments were not conducted during exploration, a dearth of data is evident in the Algoa basin, making it difficult to confirm the accuracy of a number of measurements including porosity and permeability values.

4.2. Regions with Potential CCS Reservoir Capability

The Addo Trough forms the northernmost region within the Algoa basin, preserved within a south-westward plunging half-graben structure in the Sundays River Trough. Basement depths vary from surface in the northeast to ~3700 m in the deepest portion where the half graben is bounded by the Commandokraal Fault. Ten sandstone packages have been identified with thickness varying between 30–158 m. Porosity values range between 3.4–5.8 % with sandstone permeabilities being exceptionally low <0.1 mD. Even though low porosities and permeabilities will reduce effective injection potential, five of the identified sandstone packages were considered potential reservoirs, as these occur between depths of 800–2500 m.

The Colchester Trough forms a large southeast deepening trough bounded to the north by the Colchester Fault. Within the trough two prospective reservoir regions have been identified. These are the Brak River and Colchester areas, both of which host three sandstone packages at different depths within the Kirkwood Formation. The Brak River area hosts a laterally extensive sandstone package that covers an area of ~100 km^2; however no porosity or permeability data are available for the package. Porosity and permeability data for the upper sandstone package exhibits porosities ranging between 9.91–20.2% (gas expansion), and permeability ranging between 0.6–41.2 mD (Horizontal / Liquid) and 0.7–48.5 mD (Vertical / Liquid). No porosity and permeability data are available for the Colchester borehole units; however an average porosity for borehole CO 2/67 is given as 10–12%, while for CO 3/71 it is 13% (the value used for storage capacity calculations). Cores of "clean" sandstone in CO 1/67 gave porosity values of 18% with permeabilities of 186 mD [15].

The Nanaga Structure is a faulted horst structure situated along the northeast flank of the Sundays River Trough. Five potential sandstone packages have been identified draped over the basement structure, four within the Kirkwood Formation and one in the Sundays River Formation. Sandstone porosities vary between 8% and 25%, however permeabilities are generally low, ranging between <0.1–33 mD [16]. Although exhibiting low permeabilities the structure of the region is conducive to CCS with sandstones draped as an anticlinal form above the basement structure.

Southeast of the Nanaga Structure along the eastern margin of the Algoa basin is the Seaview Anticlinal Structure within a fault-bounded half-graben. This structure holds fourteen potential reservoirs (including one that is unmappable due to data limitations). The four shallower sandstones occur within the Sundays River Formation (between depths of 745–1250 m) and the remainder within the Kirkwood Formation (at depth of 1635–2897 m). Only six packages were identified as potential reservoirs on depth characteristics, with porosity averages of 13.3% and permeability ranges of 0–3.4 mD.

The Alexandria Area is situated ~10 km east of Colchester within the coastal plain. Three sandstone packages/reservoirs of appreciable thicknesses have been identified in the area, however only two were prospective. The two potential reservoirs occur within the Sundays River Formation at depths of 1618 m and 1154 m and thicknesses of 30 m and 70 m respectively and have an average porosity of 12%.

The Springmount Area located within the confines of the Hopewell Game Reserve, host seven sandstone reservoir packages of which four are confined to the Kirkwood Formation and the rest in the Sunday River Formation. Only three of these considered as potential reservoirs (two reservoirs were too deep and the two shallower ones lacked caprock), having thickness ranges of 34–115 m. Porosity and permeability were estimated at an average of 18% and 10 mD respectively for the reservoirs in this area.

Table 3: Ranking of potential areas/sites within the Algoa basin.

Ranking (based on score)	Areas / Site	Storage potential using 1% storage coefficient (Mt)	Storage potential using 4% storage coefficient (Mt)
1	Nanaga	3.04	12.16
2	Brak River (Colchester Trough)	2.33	9.33
3	Springmount	0.81	3.24
4	Seaview	0.78	3.11
4	Addo Trough	1.11	4.46
6	Colchester Trough	0.07	0.29
6	Alexandria	0.20	0.77

5. PCSP Advisory Committee Review and Recommendations

In 2013, SACCCS assembled the PCSP Advisory Committee (PAC) to provide external technical input and review to the development of the PCSP. For the first meeting of the PAC, they were asked, based on the basin-scale assessments of the Zululand and Algoa basins, to advise on the likelihood, given the geology of the Zululand and Algoa Basins, that SACCCS will be able to identify a site for the storage of 10-50,000tCO_2, and store this volume over a maximum two year injection program. The PAC were also provided with a number of constraints to be considered including a project budget.

The PAC in their review report, complemented the depth of work done on the Algoa Basin however recommended that more information could yet be extracted from the existing data prior to deciding whether or not to progress to the acquisition of new geological data, especially given the costs associated with such data acquisition.

In particular the PAC recommended that consideration should be given to geology above 800m as this is a storage efficiency threshold only and safe storage of CO_2 above 800m is possible. They also recommended that the full newly digitized seismic data set should be reviewed and potentially chip samples from the drilling of the Algoa Basin that were not known about at the time of the basin-scale assessment. These new data should then be databased and additional analysis undertaken in the form of static and dynamic models for the formations of interest. This analysis could then be formulated into a play assessment and associated exploration plan which could, together, form a more comprehensive basis for the decision on whether or not to proceed to the acquisition of new geological data

To oversee the implementation of the recommendations put forward by the PAC review, SACCCS has established the PCSP Storage Sub-Committee (PSSC). Actions to address the recommendations are currently underway and will make use of support committed from the World Bank for their completion. Subsequent to the initial basin-scale report closure, seismic data housed at PASA has been digitized and can be re-evaluated. Research on database and software requirements and options is currently in progress.

6. Conclusions

Available data suggests that the Nanaga Structure, Colchester Trough and Seaview Area have the best potential CCS prospectivity within the Algoa basin. Due to limited and reasonably poor data availability, there is the need for new data and more tests on existing data to confirm any potential storage areas/sites.For most of the individual reservoirs, and even for some areas, insufficient information is available to make detailed capacity estimates. Lithological logs can be used to delineate further potential reservoir sandstones that are <30 m in thickness, however more detailed seismics may be needed for mapping these reservoirs. More reservoir data needs to be acquired to assist in detailed modelling of selected area(s), to include analysis (borehole core) of cap-rocks, faults, gas leakage (if any), CO_2 host rock reactions and geochemical reactions of CO_2 at depth/pressures of reservoirs at each storage area(s). Detailed and comprehensive hydrodynamic and reservoir simulations will be required. The main geological risks are the presence of possible leakage pathways and the integrity of the cap-rocks and faults. Lack of available reservoir data is a huge factor leading to uncertainties in the storage potential evaluation for the basin.

Although there is a clear lack of data available for the Algoa Basin, SACCCS is in the process of considering additional analysis of the existing Algoa data with assistance from the World Bank, and in accordance with the PAC recommendation, prior to deciding whether or not to proceed to additional data acquisition.

7. Acknowledgements

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